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Optimum design of hybrid renewable energy systems: Overview of different approaches

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ABSTRACT

Public awareness of the need to reduce global warming and the significant increase in the prices of conventional energy sources have encouraged many countries to provide new energy policies that promote the renewable energy applications. Such renewable energy sources like wind, solar, hydro based energies, etc. are environment friendly and have potential to be more widely used. Combining these renewable energy sources with back-up units to form a hybrid system can provide a more economic, environment friendly and reliable supply of electricity in all load demand conditions compared to single-use of such systems. One of the most important issues in this type of hybrid system is to optimally size the hybrid system components as sufficient enough to meet all load requirements with possible minimum investment and operating costs. There are many studies about the optimization and sizing of hybrid renewable energy systems since the recent popular utilization of renewable energy sources. In this concept, this paper provides a detailed analysis of such optimum sizing approaches in the literature that can make significant contributions to wider renewable energy penetration by enhancing the system applicability in terms of economy.

Contents

1. Introduction

Today, the world faces a great challenge for saving their future in terms of providing one of the most necessary requirements of humankind: Energy. Nowadays, a great portion of the energy requirements all around the world is supplied from conventional energy sources like coal, natural gas, crude oil, etc. [1,2]. Besides, the energy demands are increasing exponentially resulting into a rapid grow in need of conventional fossil fuels [3]. On the other hand, the mentioned conventional sources are finite and fast depleting, which in turn threatens the balance of future energy demand/generation [4,5]. Moreover, the great volatility of supply costs for the mentioned sources and negative impacts on political balances between the fuel exporting/importing countries also

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provide significant examinations on the future of conventional means of electricity production [6]. Furthermore, the energy produced by conventional energy sources increases greenhouse gas emissions which may cause global warming [5,7,8]. Thus, Kyoto agreement on global reduction of greenhouse gas emissions has been provided for preventing this issue by reducing the dependence on conventional energy systems. This situation is valid for both the developed and developing countries [9].

Achieving solution to above mentioned problems that we face today requires long-term potential actions for sustainable development. A sustainable energy system may be defined as a cost-effective, reliable, and environment friendly energy system that effectively utilizes local resources and networks [10]. For providing a sustainable energy supply, renewable energy sources appear to be the one of the most efficient and effective solutions [5,8]. Each type of renewable energy system (i.e., solar, hydroelectric, biomass, wind, ocean and geothermal energy) also has its own special advantages that make it uniquely suited to certain applications. The benefits of renewable energy penetration include a decrease in external energy dependence, decrease in transmission and transformation losses, etc. Besides, almost none of the renewable energy sources release gaseous or liquid pollutants during operation which also provide significant advantage over the conventional systems [10,11].

Even the above mentioned renewable energy systems are considered as promising power generating sources, a drawback of the mentioned energy options is their unpredictable nature and dependence on weather and climatic conditions. This issue causes the fact that renewable power production may not totally satisfy the power demand of the load at each instant [7,12–14]. This problem related with the variable nature of these resources can be solved by integrating the mentioned resources in a suitable hybrid combination which provides the potential to improve the system efficiency and the energy supply reliability [5,7,15]. Thus, the renewable energy penetration in future sustainable communities can be enhanced [13].

The mentioned hybrid systems can be configured either in stand-alone or in grid-parallel application modes. The selection of the application mode is dependent on many parameters such as grid availability, cost of grid supplied electricity, and meteorological conditions in the application site. Grid-parallel renewable energy systems that are designed to meet their local power demands are mostly utilized in urban sites. It is to be noted that large wind and solar farms, etc. that are connected to grid with a uni-directional power flow are out of scope of this study. The necessary energy when grid-parallel renewable energy systems are not sufficient to meet the load demand can be supplied by the grid. Besides, the excess energy when the renewable energy sources generates more power than the requirements during lower demand conditions as in night times, etc. are sold to grid with a pre-defined price. However, the absence of an electrical network in remote regions and the significantly high connection cost-due to large distances and irregular topography lead often the various organizations to explore alternative solutions. Stand-alone hybrid systems are considered as one of the most promising ways to handle the electrification requirements of these regions [6]. Particularly, employment of renewable energy in islands is a great opportunity to test these new technologies in stand-alone application mode [13,16]. Stand-alone applications surely require a back-up unit such as batteries, electrolyzer–fuel cell combinations, and conventional diesel generators, for reliability of the load demand supply in all operating conditions.

Even renewable energy systems provide several positive impacts for different types of application modes as defined above, the present costs of such systems prevent widespread deployment and therefore research and development efforts are concentrated on accelerated cost reductions and efficiency improvements of these systems [2]. In order to obtain electricity from a renewable energy based hybrid system reliably and at an economical price, its design must also be optimal in terms of operation and component selection [17,18]. Thus, an optimum sizing method is quite necessary in order to efficiently and economically utilize the renewable energy resources [6]. Particularly, the optimum sizing of such systems requires detailed analysis for a given location due to the influence of various site-dependent variables such as solar radiation, wind speed, and temperature and their relation to the system cost [7,19]. The computation power of modern computers is increasing dramatically and hence the computer-based simulation and optimization have received more and more attention, and becoming an important tool for the design of the power systems requiring a detailed analysis [20].

Various optimization techniques for hybrid system sizing have been reported in the literature such as genetic algorithm (GA), simulated annealing (SA), and particle swarm optimization (PSO). Besides, several sizing tools such as Hybrid Optimization Model for Electric Renewables (HOMER) have been developed and widely utilized in many applications. This paper reports the throughout review for presenting the state-of-art of hybrid system sizing approaches. Thus, it is aimed that this paper may be useful for researchers to understand the recent trends about optimum sizing of renewable energy based hybrid systems.

The organization of this paper is as follows. Section 2 presents the available software tools and optimization based sizing algorithms taking place in the current literature. Section 3 discusses the possible promising methodologies for future use in hybrid renewable energy system sizing. Finally, conclusions are given in Section 4.

2. Sizing approaches in the current literature

The optimum design of hybrid renewable energy systems is a hot topic and there is a rich literature dedicated to this topic. The mentioned design problem to be formulated is related to the determination of the optimal configuration of the power system and optimal location, type and sizing of generation units installed in certain nodes, so that the system meets load requirements at minimum cost [21]. The design of the hybrid renewable energy systems can be evaluated through its lifetime cost and emission. The lifetime cost typically consists of two other components in addition to the operational cost. These components include the capital cost and the maintenance cost, together referred to as the “fixed cost”. In calculation of the lifetime cost, changes in the monetary value due to time must also be taken into consideration. Thus, the optimal hybrid system configuration seeks a combination of generator types and sizes that result in the lowest lifetime cost and/or emission. Among all possible hybrid system configurations that are optimally dispatched, the configuration with the lowest “Net Present Value (NPV)” is declared as the “optimal configuration” or the “optimal design” [22,23].

There are many approaches for providing this mentioned “optimal design” criteria. Many software tools are commercially available that can be helpful for real time system integration. Besides, several optimization techniques have also been applied by many researchers for the sizing of hybrid renewable energy systems. The evaluation of the mentioned approaches is given in following subsections.

2.1. Commercially available software tools for hybrid system sizing

Simulation programs are the most common tools for evaluating performance of the hybrid renewable energy systems. Currently,

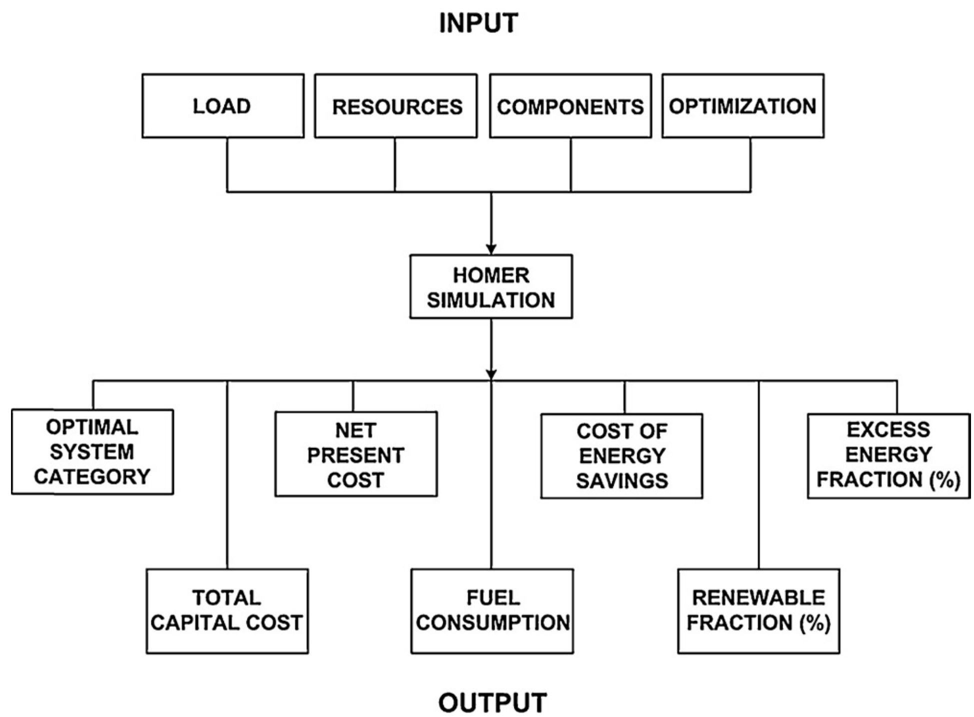

Fig. 1. Architecture of HOMER software.

there are many software programs available that can be downloaded from the websites of several research laboratories and universities. By using the mentioned simulation programs, the optimum configuration can be found by comparing the performance and energy production cost of different system configurations. Among them, one of the most famous sizing programs for hybrid systems is HOMER developed by National Renewable Energy Laboratory (NREL), United States [24].

HOMER includes several energy component models, such as photovoltaics (PVs), wind turbines, hydro, batteries, diesel and other fuel generators, electrolysis units, and fuel cells, and evaluates suitable options considering cost and availability of energy resources [25]. Grid connection is also considered in HOMER design procedure. The software requires initial information including energy resources, economical and technical constraints, energy storage requirements and system control strategies. Inputs like component type, capital, replacement, operation and maintenance costs, efficiency, operational life, etc. are also required [3]. The architecture of the software is presented in Fig. 1 [26–28].

HOMER has widely been used in previous renewable energy system case studies taking place in the literature. Both grid-parallel and stand-alone systems have been investigated. Besides, the parallel combination of renewable energy sources and conventional systems such as diesel generators has also been considered in many studies. The papers in the literature dealing with optimum sizing of hybrid systems using HOMER are referred in [3,5,23,26,27,29–61].

Several more software tools are also available for designing of hybrid systems, such as “The Hybrid Power System Simulation Model (HYBRID2)” [62], “The General Algebraic Modeling System (GAMS)” [63], “Optimization of Renewable Intermittent Energies with Hydrogen for Autonomous Electrification (ORIENTE)” [64], OptQuest [65,66], LINDO [67,68], WDILOG2 [69], “Dividing Rectangles (DIRECT)” [70,71], “Determining Optimum Integration of RES (DOIRES)” [72], “Simulation of Photovoltaic Energy Systems (SimPhoSys)” [73], “Geo-Spatial Planner for Energy Investment Strategies (GSPEIS)” [74,75], “Grid-connected Renewable Hybrid Systems Optimization (GRHYSO)” [76], and H_2RES [77]. For a detailed literature survey specifically on commercially available software tools for the performance evaluation of hybrid renewable energy systems, the readers are addressed to Ref. [78].

2.2. *Optimization techniques for hybrid renewable energy system sizing*

2.2.1. *Genetic algorithm*

GA is an optimization method based on the genetic process of biological organisms [79,80]. By mimicking this process, GA has capability to provide solutions to complex real world problems. The concept of GA was firstly proposed by Holland [81] and then widely utilized in many types of applications.

The use of GA in sizing of energy systems can be summarized as presented in Fig. 2. As seen from Fig. 2, the input data of GA-based methodology can be the meteorological conditions and the unit prices of the projected hybrid system components including installation and maintenance costs. Some constraints can also be added to the algorithm. Example constraints can be given as limiting the maximum number of PV panels on a building roof that is constrained by roof area, limiting the number wind turbines installed on specific land constrained by land area, or limiting the power change slope of a fuel cell, etc. Many different constraints can be defined due to the type of application. Besides, a fitness function must be defined as an input to the GA approach. Moreover, the parameters for GA operators such as the percentage of selection and rate of mutation should be provided before the GA-based sizing process. With the given input data, GA-based sizing methodology provides an iterative procedure utilizing the GA operators until a predefined termination criteria or maximum iteration number are reached. A basic GA consists of five components. These are an initial random population generator, a “fitness” evaluation unit and genetic operators for “selection”, “crossover” and “mutation” operations [82,80,79]. With the random population generation at the start, GA algorithm offers random sizes for the hybrid system components that satisfy the load demand/power generation balance at each step. Each of the random solutions is evaluated according to

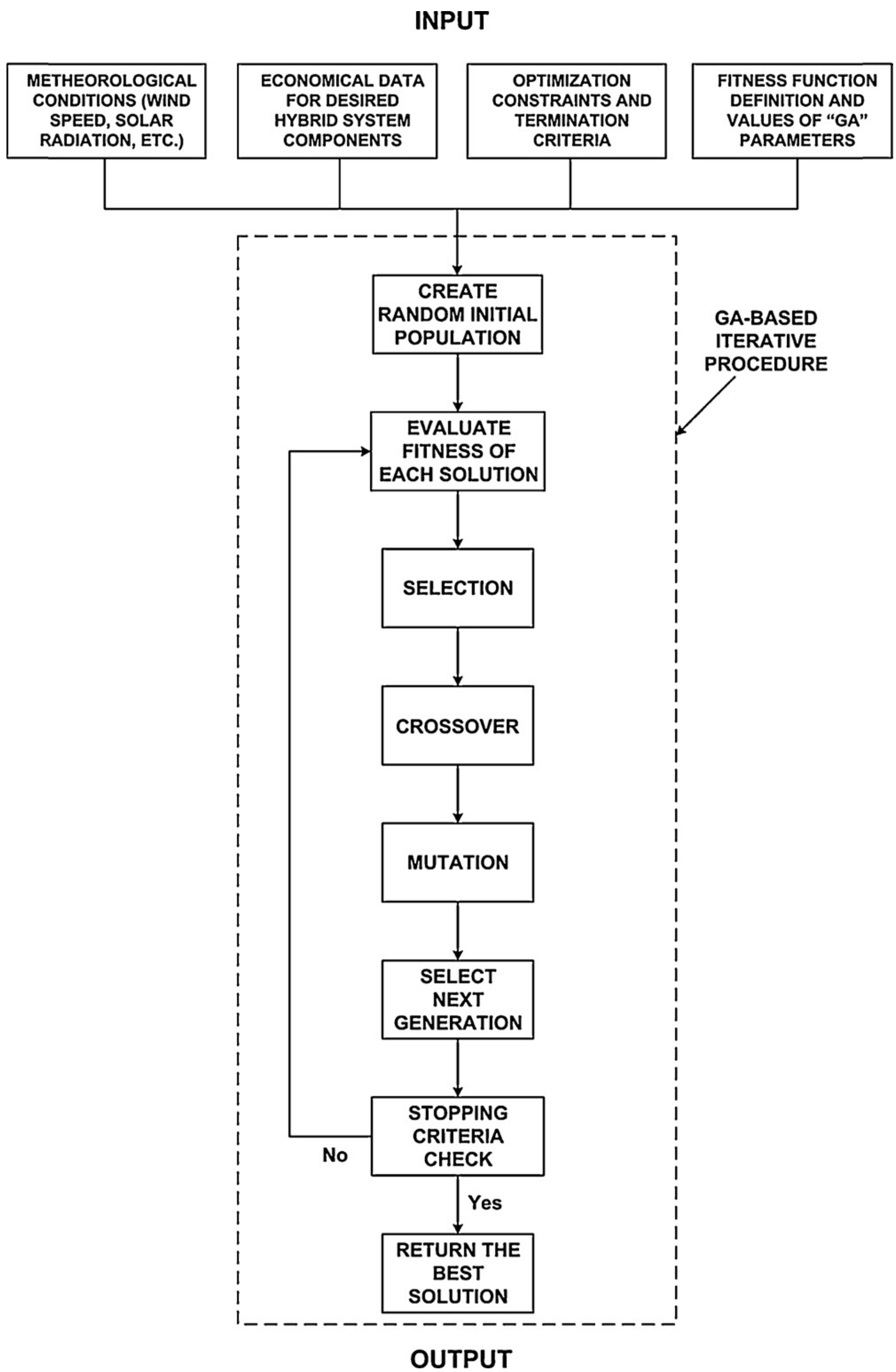

Fig. 2. GA flowchart.

the defined fitness function. "Selection" operator selects the predefined percentage of the initial population due to their fitness value [83,84]. Utilizing these selected solutions, "crossover" operator provides new possible solutions with the aim of achieving higher fitness values. For example, for a PV–wind–fuel cell hybrid system, the selection operator may choose two different solutions of 10/20/15 (10 kW wind turbine, 20 kW PV system, 15 kW fuel cell) and 5/25/12 (5 kW wind turbine, 25 kW PV system, 12 kW fuel cell). With an example crossover operation, two new possible solutions that can either have a lower or greater fitness value than current solutions can be provided as 5/25/15 (5 kW wind turbine, 25 kW PV system, 15 kW fuel cell) and 10/20/12 (10 kW wind turbine, 20 kW PV system, 12 kW fuel cell). The new population is created with the solutions selected by the "selection" operator and the new solutions created by the "crossover" operator. Then, the selection of the solutions with greater fitness values and creation of a new population continue at each iteration during the iterative procedure. During the iterative process, a "mutation" operator can also be applied to prevent getting stuck at a local minimum. As an example, changing the fuel cell size from 15 kW to 5 kW in a 10/20/15 solution (10 kW

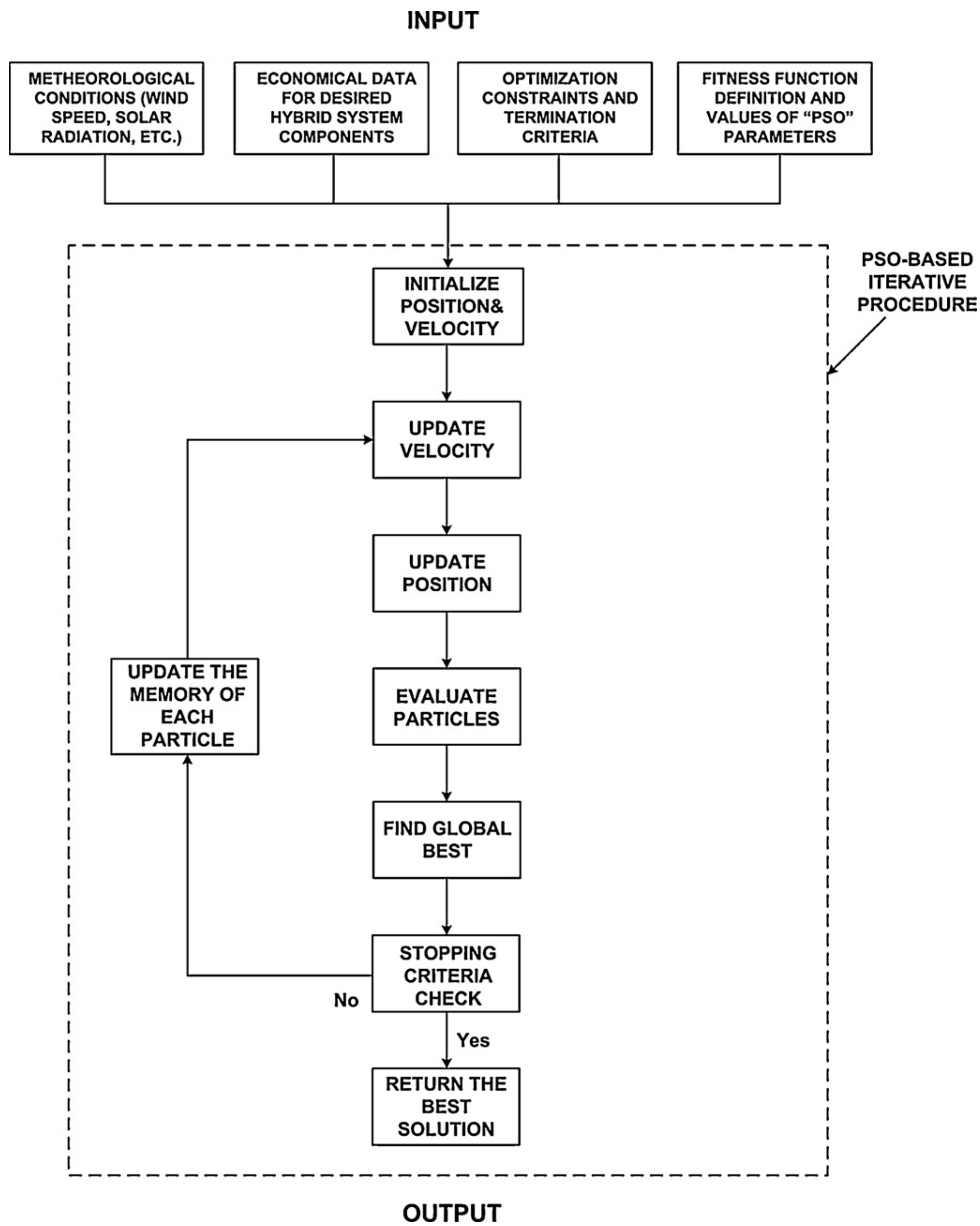

Fig. 3. PSO flowchart.

wind turbine, 20 kW PV system, 15 kW fuel cell) can be provided by the mutation operator. This procedure consisting of the selection, crossover and mutation cycle continues until the termination of the iterative process [85–88].

The most significant advantage of GA for use in hybrid system sizing is that it can easily jump out of a local minimum and has quite efficient capability to find the global optimum. Besides, the advantage of being able to code infinite number of parameters on a chromosome makes it suitable for sizing studies. This advantage is not available in some other mostly utilized approaches like PSO, etc. that will be described below. As an example, especially for a hybrid system consisting of more than three components (such as PV–wind–fuel cell–hydro hybrid system), the use of GA comes into prominence as PSO can be coded for three parameters at most that will be evaluated in the next subsection. Besides, GA approach does not require derivative information. However, the GA is relatively harder to code due to its complex structure. Moreover, if the number of parameters becomes larger, the GA structure becomes more complex and the response time of GA increases quite significantly [89–92].

Due to the presented advantages, GA has widely been used in several cases and information regarding its use can be found in many published articles dealing with the hybrid system sizing studies. Among them, Koutroulis et al. [93,94], Yang et al. [95,96] and Bilal et al. [97] utilized GA for sizing of a stand-alone hybrid PV–wind system. Lagorse et al. [98] applied GA to economically design a multisource hybrid unit composed of PV, wind and fuel cell. A more detailed system consisting of PV, wind, fuel cell, microturbine and battery was optimally sized by Kalantar et al. [99] using GA. Lopez et al. [100,101] developed a simulation program named Hybrid Optimization by Genetic Algorithms (HOGA) based on utilization of GA in order to design different combinations of stand-alone hybrid energy systems including renewable energy sources as well as conventional diesel generator. A hybrid

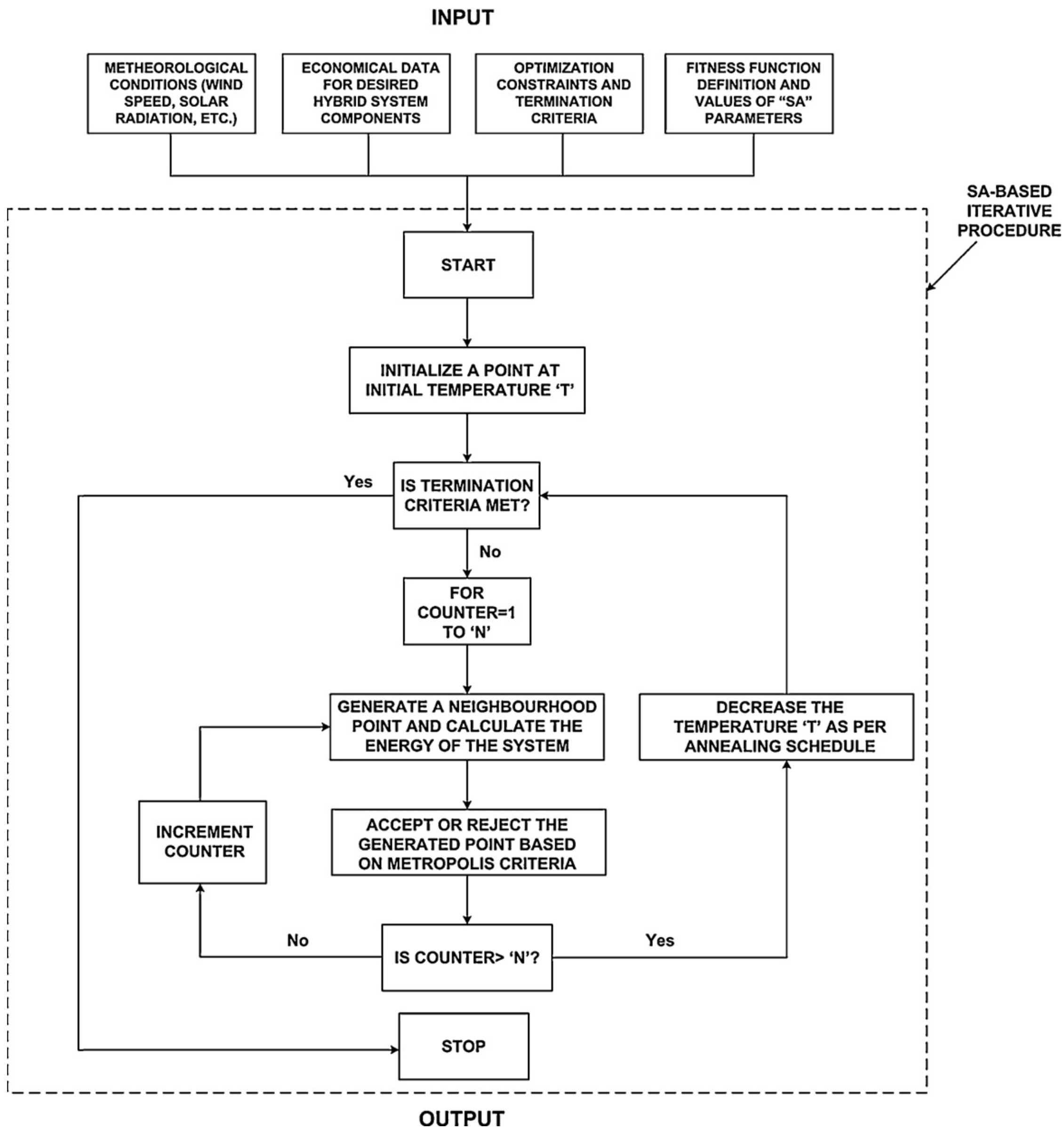

Fig. 4. SA flowchart.

GA&simplex based methodology was employed by Lagorse et al. [102]. GA was utilized in several more studies including Refs. [103–114] for different kinds of hybrid energy systems. As clearly seen, GA has a significant area in hybrid system sizing studies.

2.2.2. Particle swarm optimization

PSO is an optimization technique based on the movement and intelligence of swarms and belongs to evolutionary computation techniques. It was developed in 1995 by James Kennedy (social-psychologist) and Russell Eberhart (electrical engineer). Particle swarm is the system model or social structure of basic creature which makes a group to have some purpose such as food searching [115,116].

The PSO structure in hybrid system sizing studies can be summarized as seen in Fig. 3. Similar to GA-based approach, the input data of PSO-based methodology are the meteorological conditions, the unit prices of the projected hybrid system components including installation and maintenance costs, predefined constraints and fitness function and the values of specific PSO parameters as seen from Fig. 3. The process of PSO-based sizing methodology is a population-based stochastic optimization procedure. Each potential solution in PSO population is called as a particle [117,118]. In PSO, the co-ordinates of each particle represent a possible solution associated with position and velocity vector. Each particle is initialized by a random velocity and is flown through the search space. At each iteration, particle move towards an optimum solution, through its present velocity, personal best solution obtained by themselves so far and global best solution obtained by all particles [119,120]. As an example to better examine the process of PSO approach, a hybrid PV–wind system can be evaluated. For example, the current position of a particle in search space at iteration "i" is assumed as 15, 20 (15 kW wind turbine, 20 kW PV system) on x–y diagram. Besides, the current position of the particle having the best fitness value among all population at the current iteration is assumed as 25, 20 (25 kW wind turbine, 20 kW PV system). It is also assumed in PSO that all the particles in the population have great knowledge on the current positions of its neighbours and the particle having the best position. Thus, the particle at 15, 20 position examines the search area and increases its current velocity on the x axis to reach the particle with the best position at 25, 20. All

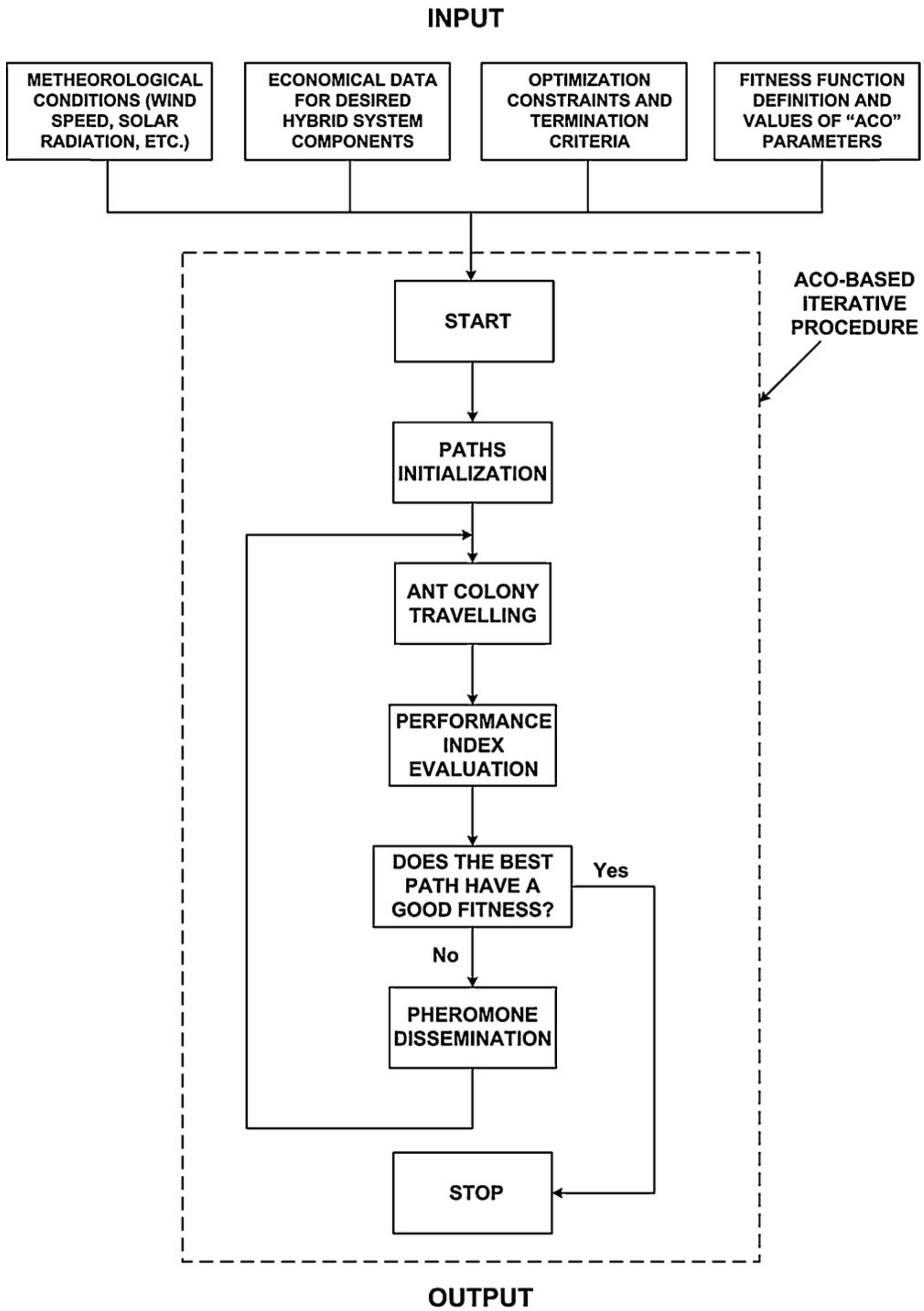

Fig. 5. ACO flowchart.

the particles in the population apply the same procedure at each iteration and thus a group movement is reached with this process. The iteration procedure continues until a pre-defined termination criteria is reached [121,122].

Although both GA and PSO algorithms have excellent efficiency with using similar iterative searching methods, the PSO has some advantages over GA. One of the most important features of this approach is that it is based on a simple concept involving few equations that are easy to implement in a software environment. Therefore, the computation time is short and it requires few memories [8,123]. However, the reliability for finding the global optimum of a search area is lower than GA-based approach. Besides, the PSO approach is less suitable than GA for problems consisting of more than three parameters as PSO is based on coordinate definition of particles and the mentioned coordinates can only be defined on *x*, *y*, *z* plane (For example if a PV–wind–fuel cell hybrid system is considered and only the sizes of the mentioned system is to be optimized, than *x*-axis may be used to present the number of PV panels, the *y*-axis may present number of wind turbines and the *z*-axis may be related to power of fuel cell system in kW). Thus, below three components, the use of PSO can be more efficient than GA. However, if more than three components are available, it is more applicable to utilize GA approach instead of PSO as mentioned before.

Similar to GA approach, PSO also has a wide use in hybrid system sizing studies and it is easy to find literature examples like GA. Sanchez et al. [121], Denghan et al. [122] and Kaviani et al. [124] proposed a PSO-based unit sizing methodology for PV–wind–fuel cell microgrids. A wind–fuel cell based structure was considered

Table 1
Brief comparison of main approaches applied for the sizing of hybrid renewable energy systems in the literature.

Energy management approach	Advantages	Disadvantages	Literature studies
HOMER	Makes it easy to understand the main concepts of a sizing procedure with efficient output figures, it can be downloaded freely	“Black Box” code utilization, first degree linear equations based models for hybrid system components that do not represent the source characteristics exactly	[3,5,23,26,27,29–61]
Other software tools (HYBRID2, etc.)	The advantage changes from software to software, most of them can be downloaded freely	Most of them have “Black Box” code utilization, each of them has its own disadvantage	[62–77]
Genetic algorithm	Efficient performance for finding the global optimum, easy to find literature examples, suitable for complex problems with great number of parameters	Relatively harder to code	[93–114]
Particle swarm optimization	Easy to code with few equations, easy to find literature examples	Relatively lower performance for finding the global optimum compared to GA, etc., not suitable for complex problems with great number of parameters	[8,116,118,120–132]
Simulated annealing	Easy to code, easy to find literature examples	Relatively lower performance for finding the global optimum compared to GA, etc., not efficient for complex problems with great number of parameters	[15,138]
Linear programming	Easy to code	Computational time inefficiency	[21,139–142]
Evolutionary algorithm	Efficient performance for finding the global optimum	Relatively harder to code	[143–147]
Neural networks	Efficient performance in most type of applications, easy to find literature examples	Needs a training procedure	[148–150]
Simplex algorithm	Easy to understand	Relatively lower performance for finding the global optimum compared to GA, etc.	[102,151,152]
Stochastic, iterative, probabilistic, parametric and numerical approaches	Easy to implement and understand	Computational time inefficiency	[9,12,45,154–169,185–194]
Design space based approach	Easy to implement and understand	Computational time inefficiency	[170–184]
Other approaches (matrix approach, etc.)	The advantage changes from approach to approach	Harder to find literature examples	[153,195]

by Tafreshi and Hakimi [125,126]. A wind–PV hybridization and unit sizing with PSO were proposed by Wang and Singh [127] and Zhao et al. [128]. Wang and Singh [129] utilized PSO for grid parallel hybrid renewable energy systems. PSO was utilized in some more studies aiming to techno-economically design hybrid renewable energy systems. To investigate these studies, the readers are addressed to Refs. [8,116,118,120,123,130–132].

2.2.3. Simulated annealing (SA)

The SA is a general optimization technique for solving combinatorial optimization problems that was introduced by Kirkpatrick et al. [133]. A solid in a heat bath is heated up by increasing the temperature of the heat bath and then cooled through slowly lowering the temperature of the heat bath in the annealing process [133].

The basic algorithm of SA for hybrid system sizing applications may be described with the flowchart presented in Fig. 4. At each iteration, a candidate move is randomly selected and this move is accepted if it leads to a solution with a better objective function value than the current solution. Otherwise the move is accepted with a probability that depends on the deterioration of the objective function value based on “Metropolis criteria”. For example, the hybrid PV–wind system considered in PSO can be examined again. The current best solution in the population at iteration “*i*” is assumed to be 25/20 (25 kW wind turbine, 20 kW PV system). Another new solution in the population is also assumed as 15/20 (15 kW wind turbine, 20 kW PV system). If this new solution has a better fitness value than the current best solution in the population, then the new solution is accepted. On the other hand, if this new solution has a worse fitness value than the current best solution in the population, then the new solution may also be accepted and considered for the new population at the next iteration depending on the difference between its fitness value and the best fitness value. The annealing procedure depending on the temperature decrement allows for wide area searches by a faster temperature decrement at the beginning of the iterative process, then local area searches around the best solutions in the wide area search steps with slower temperature decrement in the next steps of the algorithm. The temperature decrement procedure is called “cooling schedule”, which is the main structure of the SA approach [134–137].

The use of SA in hybrid system sizing is not so popular as GA or PSO, but the mentioned area of use is growing nowadays with the increasing interest of researchers on SA. The studies of Ekren and Ekren [15] for wind–PV–battery hybridization and Giannakoudis et al. [138] for a renewable-hydrogen storage combination based hybrid system can be given as examples from the literature.

2.2.4. Other methods utilized in the literature

Various approaches in addition to above given methodologies such as linear programming [21,139–142], evolutionary algorithms [143–147], neural networks [148–150], simplex algorithm [102,151,152], dynamic programming [153], stochastic approach [154,155], iterative and probabilistic approaches [9,12,45,156–169], design space based approach [170–184], parametric and numerical approaches [185–194], response surface methodology [195,196], matrix approach [197], quasi-Newton algorithm [198], and “Energy hub” concept [199] have been utilized by researchers to design hybrid renewable energy systems in a cost effective way. Several more algorithms also seem promising to enrich the literature dedicated to hybrid energy system sizing. Table 1 shows a brief evaluation of the above mentioned sizing approaches taking place in the literature.

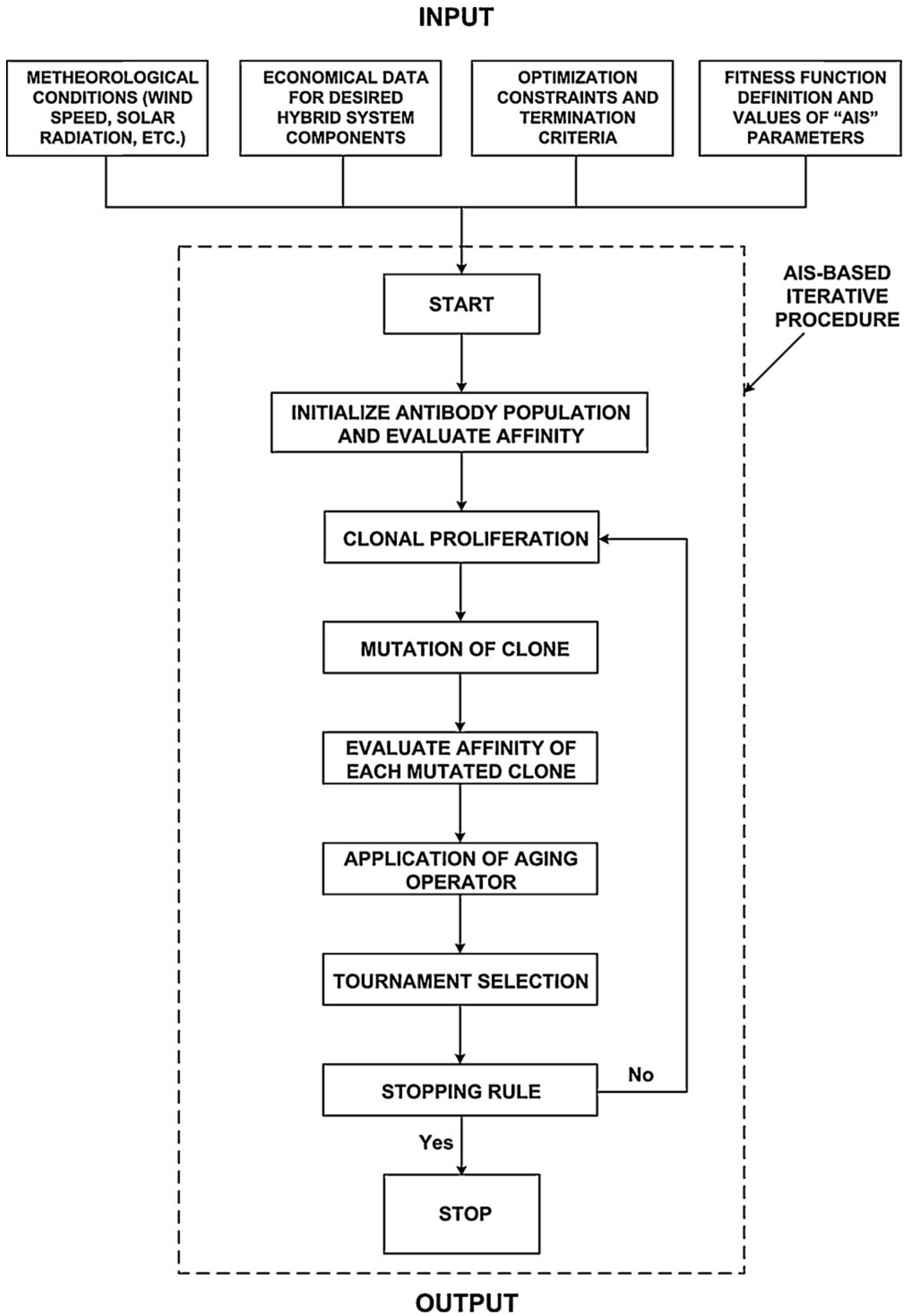

Fig. 6. AIS flowchart.

3. Possible promising techniques for future use in hybrid system sizing

3.1. Ant colony algorithm

Ant colony optimization (ACO) is a technique for optimization that was introduced in 1990s by Marco Dorigo and his colleagues [200,201]. The development of this algorithm was inspired by the observation of ant colonies. After several observations, it has been realized that the larger is the number of colonies using a specific path for finding food, the larger the probability that the same path will be utilized in future [202,203]. Several scientists studied such behavior and revealed a key point that the presence of an ant-specific pheromone is used to mark a path. [204]. The smell of the pheromone is vanishing and, as a consequence, if a path is not utilized any more, its smell will get weaker. Thus, the probability of this path to be used in future will decrease. The stronger is the pheromone smell, the larger is the number of attracted ants to go along it [205,206]. Best paths are next to the food since many more ants are next to good and rich places and all together they contribute to increase the pheromone level of those paths leading to the food. The best path (it can also be called as "shortest path") towards the food in the proposed application is the highest possible value of performance index in an optimization procedure [207].

A block diagram of the ACO approach that can be helpful for upcoming researchers focused on hybrid system sizing is shown in Fig. 5 [200]. In the search space, each ant is initially placed in a separate random place. The current coordinates of an ant in the search area can be given in x–y plane like the PV–wind example in Section 2.2.2. The current position of the mentioned ant is assumed to be 15, 20 (15 kW wind turbine, 20 kW PV system). This ant smells the pheromone around its position and moves through a second place with highest pheromone level at the next iteration. This next movement may be realized to 14, 20 (14 kW wind turbine, 20 kW PV system), 16, 20 (16 kW wind turbine, 20 kW PV system), 15, 21 (15 kW wind turbine, 21 kW PV system) and 15, 19 (15 kW wind turbine, 20 kW PV system) considering the pheromone level in these possible options. Like this ant, all of the ants in the colony search around their positions and select their next movement due to pheromone level. Thus, all the search area is considered and the colony starts to move as a group in the next levels of the iterative procedure. As long as pre-defined conditions are reached like the desired rate of ants finding the food space or maximum number of iterations, the algorithm is terminated and the results are presented [201,202].

ACO is promising for future applications and may obtain a significant place especially in areas with similar group movement based algorithms like PSO, etc. The above given advantages and disadvantages for PSO approach described in Section 2.2.2 are also valid for ACO. For lower number of parameters (for example not more than three parameters as the positions of ants are also described in x, y, z planes as in PSO), the use of ACO may significantly increase in future for hybrid system sizing studies.

3.2. Artificial immune system algorithm

Artificial immune system (AIS) algorithm is proposed in the 1990s as a new branch in computational intelligence. AIS is inspired by immunology, immune function and principles observed in nature [208]. The immune system is an important self-defense method that guards the human body from foreign antigens or pathogens such as viruses and bacteria. To perform this function, the immune system has to be able to distinguish between the own cells of body as the self cells and foreign pathogens as the non-self cells or antigens. After distinguishing between self and non-self cells, the immune system has to perform an immune response in order to eliminate non-self cell or antigen [209–211].

AIS based optimization procedure for hybrid system sizing can be realized on such a flowchart shown in Fig. 6. The solutions in the search space can be coded as antigen population in the AIS algorithm. The structure of the antigen population changes at each iteration with the evaluation of the population performance during elimination of the infeasible solutions (pathogens). Old antigens with lower fitness values (affinities) are replaced with new ones in order to maximize the group fitness value. Similar to GA, AIS based optimization includes “selection” and “mutation” operators that can significantly enhance the probability of the algorithm to find the global optimum point [208,210,211]. The PV–wind–fuel cell example given in Section 2.2.1 for GA is similarly valid for AIS approach.

Due to its similarity with GA for possible effective performance for finding the global optimum of complex problems, AIS has great potential to be used for sizing studies in the near future. However, the applicability of GA is still greater than AIS due to its ability to deal with large number of parameters.

3.3. Other promising approaches

Many more approaches that can be utilized in the future studies in order to efficiently and economically size hybrid energy systems take place in the literature. Among them, tabu search [212,213], honey bee mating algorithm [214,215], bacterial foraging algorithm [216,217], and game theory [218,219] can be proposed as the mostly utilized methods in other kinds of applications.

4. Conclusions

Increase of the global energy demand and environmental problems relating to fossil energy utilization have promoted the widespread research on renewable energy technologies to replace the traditional fossil fuels. Particularly, hybrid systems, which may be defined as a combination of renewable and back-up units or conventional energy sources, become an applicable solution to the challenges that the world faces today for sustainability issue of energy supply and environmental protection.

Due to the topography of the area, energy resources potential available and type of energy requirements, the hybrid energy systems can be developed and optimized in order to suit the needs of the area. The optimal sizing of these renewable energy based hybrid systems can significantly improve the economical and technical performance of power supply as well as promoting the widespread use of such environment friendly sources. Different sizing methods can be applied to reach a techno-economically optimum hybrid renewable energy system. Thus, economical barriers for better penetration of renewable energy can be partly overcome. Several sizing methodologies including available softwares as well as potential different optimization techniques are examined in the content of this paper. As stated before, each sizing methodology has its own features and many more new methodologies have potential for future use in this aspect. The selection of the suitable approach may change due to the type of application, user requirements, etc. In short, each developed sizing approach has potential to significantly promote the applicability of renewable energy systems and thus, has a great importance in renewable energy area.

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